

Draft version from February 1, 2008

Outflow and dense gas emission from massive Infrared Dark Clouds

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ABSTRACT

Infrared Dark Clouds are expected to harbor sources in different, very young evolutionary stages. To better characterize these differences, we observed a sample of 43 massive Infrared Dark Clouds, originally selected as candidate high-mass starless cores, with the IRAM 30 m telescope covering spectral line tracers of low-density gas, high-density gas, molecular outflows/jets and temperature effects. The SiO(2–1) observations reveal detections toward 18 sources. Assuming that SiO is exclusively produced by sputtering from dust grains, this implies that at least in 40% of this sample star formation is on-going. A broad range of SiO line-widths is observed (between 2.2 and 65 km s^{−1}), and we discuss potential origins for this velocity spread. While the low-density tracers ¹²CO(2–1) and ¹³CO(1–0) are detected in several velocity components, the high-density tracer H¹³CO⁺(1–0) generally shows only a single velocity component and is hence well suited for kinematic distance estimates of IRDCs. Furthermore, the H¹³CO⁺ line-width is on average 1.5 times larger than that of previously observed NH₃(1,1). This is indicative of more motion at the denser core centers, either due to turbulence or beginning star formation activity. In addition, we detect CH₃CN toward only six sources whereas CH₃OH is observed toward approximately 40% of the sample. Estimates of the CH₃CN and CH₃OH abundances are low with average values of 1.2×10^{-10} and 4.3×10^{-10} , respectively. These results are consistent with chemical models at the earliest evolutionary stages of high-mass star formation. Furthermore, the CH₃OH abundances compare well to recently reported values for low-mass starless cores.

Subject headings: stars: formation – stars: early-type – ISM: jets and outflows – ISM: abundances – ISM: clouds – ISM: kinematics and dynamics

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1. Introduction

While observational research in high-mass star formation over the last few decades has focused on relatively evolved regions like Ultracompact HII regions (UCHIIs) and High-Mass Protostellar Objects (HMPOs) (e.g., see reviews by Kurtz et al. 2000; Churchwell 2002; Beuther et al. 2007), the earliest stages of massive star formation have become regularly accessible only through the advent of large-scale mid-infrared surveys of the Galactic plane by satellite missions like the Infrared Space Observatory (ISO), the Midcourse Space Experiment (MSX) and most recently Spitzer. The basic observational characteristics of the earliest stages of (massive) star formation, prior to the formation of any embedded heating source, should be that they are strong cold dust emitters at (sub)mm wavelengths, and weak or non-detections in the mid-infrared because they have not yet heated a warm dust cocoon. In the low-mass regime, so-called Infrared Dark Clouds (IRDCs) have been studied regularly since a few years (e.g., Egan et al. 1998; Carey et al. 2000; Bacmann et al. 2000), in high-mass star formation the focus has shifted to these objects only more recently (e.g., Sridharan et al. 2005; Hill et al. 2005; Klein et al. 2005; Simon et al. 2006; Beltrán et al. 2006; Rathborne et al. 2006; Pillai et al. 2006).

Massive IRDCs (in short IRDCs from now) are not a well defined class, but they likely harbor various evolutionary stages, from genuine High-Mass Starless Cores (HMSCs) via High-Mass Cores harboring accreting Low/Intermediate-Mass Protostars to the youngest HMPOs (Beuther et al. 2007). While the first stage provides good targets to study the initial conditions of massive star formation prior to cloud collapse, the other stages are important to understand the early evolution of massive star-forming clumps. Here, we are targeting a sample of massive IRDCs first identified as candidate HMSCs by Sridharan et al. (2005) to differentiate between the different evolutionary stages existing within this sample. To facilitate this, we observed the target sample with the IRAM 30 m telescope in different spectral lines sensitive to various physical processes like molecular outflows (e.g., SiO, CO), dense gas (e.g., H^{13}CO^+ , CH_3CN , CH_3OH) or hot core conditions (CH_3CN , CH_3OH). Table 1 lists the observed spectral lines, the upper level excitation energies E_{upper} and the critical densities n_{crit} .

2. Observations and Data Reduction

We observed a sample of 43 IRDCs selected from Sridharan et al. (2005) in August 2005 at the IRAM 30 m telescope on Pico Veleta with four receivers simultaneously. The flexible multi-receiver setup of the 30 m telescope allowed us to observe usually a few lines within the same spectral setup of each receiver ((1) $\text{H}^{13}\text{CO}^+(1-0)$ & $\text{SiO}(2-1)$, (2) $^{13}\text{CO}(1-0)$ and

CH₃CN, (3) ¹²CO(2–1), (4) CH₃OH). Table 1 lists the corresponding frequencies, the spectral resolution and the system temperatures for each line. The observations were conducted in a position-switching mode with OFF positions carefully chosen from the Massachusetts-Stony Brook Galactic plane CO survey (Sanders et al. 1986), usually approximately of the order 1000'' offset from the source positions.

Table 1: Observing parameters

Line	Freq. GHz	Δv km s ^{−1}	T_{sys}^a K	1σ rms ^a K	E_{upper} K	n_{crit}^b cm ^{−3}
H ¹³ CO ⁺ (1–0)	86.754	1.1	110	0.02	4.2	1.7e5
SiO(2–1)	86.847	1.1	110	0.02	6.3	7.3e5
¹³ CO(1–0)	110.201	0.9	220	0.04	5.3	2.2e3
CH ₃ CN(6 ₀ – 5 ₀)	110.384	0.9	220	0.03	18.5	1.5e6 ^c
CH ₃ CN(6 ₁ – 5 ₁)	110.381	0.9	220	0.03	25.7	1.5e6 ^c
CH ₃ CN(6 ₂ – 5 ₂)	110.375	0.9	220	0.03	47.1	1.6e6 ^c
¹² CO(2–1)	230.538	1.6	660	0.30	16.6	1.0e4
CH ₃ OH(5 ₁ – 4 ₁)E	241.879	1.2	760	0.13	55.9	1.1e6
CH ₃ OH(5 ₀ – 4 ₀)A+	241.791	1.2	760	0.13	34.8	^d
CH ₃ OH(5 _{−1} – 4 _{−1})E	241.767	1.2	760	0.13	40.4	9.5e5
CH ₃ OH(5 ₀ – 4 ₀)E	241.700	1.2	760	0.13	47.9	1.0e6

^a Average system temperature and 1σ rms values.

^b Calculated from $A = 0.3\lambda_{100}^{-3}\mu^2$ (λ_{100} in units of 100 μ m and $\mu = 3.9$ debye) and $\gamma(\text{CH}_3\text{CN}(6-5))_{20\text{K}}$ from Pei & Zeng (1995b,a).

^c $n_{\text{crit}} = A/\gamma$ with the Einstein coefficient A and the collisional rate γ . Except for CH₃CN, A and γ were taken from LAMBDA (Schöier et al. 2005) at $T = 20$ K.

^d No data for this transition in LAMBDA.

3. Results and discussion

3.1. ¹²CO(2–1), ¹³CO(1–0) and H¹³CO⁺(1–0)

Figures 1, 2 and 3 show the ¹²CO(2–1), ¹³CO(1–0) and H¹³CO⁺(1–0) spectra for the whole source sample. Except of IRDC 18431-0312-4, where the H¹³CO⁺(1–0) line remained undetected, toward all other sources the three lines were detected. The most obvious difference between ¹²CO/¹³CO on the one side and H¹³CO⁺ on the other side is that the

CO isotopologues are detected at many different velocities whereas H^{13}CO^+ usually only shows a single spectral peak (except of a few double-peaked structures listed in Table 2). This difference can be explained straightforwardly by the location of the sources within the Galactic plane because CO traces more or less all molecular clouds along the line of sight, hence contributions from various Galactic spiral arms, whereas H^{13}CO^+ has significantly higher critical densities (Table 1) and thus traces only the dense cores we are interested in. Therefore, if one wants to know the velocity of a specific region CO observations are mostly not useful and one has to refer to high density tracers. The peak velocities v of H^{13}CO^+ (Table 2) correspond well to the previously derived velocities from NH_3 observations of the same sample (Sridharan et al. 2005). Identifying the correct associated velocity component to derive accurate velocities is an important step to get distance estimates from the Galactic rotation curve as reported in Brand & Blitz (1993) and Sridharan et al. (2005).

Table 2 also lists the Full Width Half Maximum (FWHM) line-widths $\Delta v(\text{H}^{13}\text{CO}^+)$ of the observed H^{13}CO^+ lines from Gaussian fits, the average H^{13}CO^+ line-width is 2.6 km s^{-1} . Figure 4 shows a comparison of the H^{13}CO^+ line-width with the previously derived line-width from the $\text{NH}_3(1,1)$ observations from (Sridharan et al. 2005). We find that the H^{13}CO^+ line-width nearly always exceeds the line-width from the $\text{NH}_3(1,1)$ with an average line-width ratio $\frac{\Delta v(\text{H}^{13}\text{CO}^+(1-0))}{\Delta v(\text{NH}_3(1,1))} = 1.5$. This is interesting since the critical densities for both molecules differ by about 2 orders of magnitude ($n_{\text{crit}}(\text{NH}_3(1,1)) \sim 2 \times 10^3 \text{ cm}^{-3}$, e.g. Zhou et al. 1989, $n_{\text{crit}}(\text{H}^{13}\text{CO}^+(1-0)) \sim 1.7 \times 10^5 \text{ cm}^{-3}$, Table 1), whereas the thermal line-widths ($\Delta v_{\text{th}} = \sqrt{8 \ln 2 \frac{kT}{m_{\text{mol}}}}$ with the molecular mass m_{mol}) are similar ($\Delta v_{\text{th}}(\text{NH}_3(1,1))_{15\text{K}} \sim 0.2 \text{ km s}^{-1}$ and $\Delta v_{\text{th}}(\text{H}^{13}\text{CO}^+(1-0))_{15\text{K}} \sim 0.15 \text{ km s}^{-1}$), $\Delta v_{\text{th}}(\text{H}^{13}\text{CO}^+(1-0))$ being even smaller than $\Delta v_{\text{th}}(\text{NH}_3(1,1))$ because of its larger molecular weight. Therefore, differences in the non-thermal motions have to be responsible for the line-width variations between both species. Similar results were obtained for low-mass cores in a comparison of CS with NH_3 line-widths (Zhou et al. 1989).

There exist several potential ways to explain such a line-width difference. For example, there is the well-known line-width–size relation $\Delta v \propto R^{0.5}$ (Larson 1981). This relation would imply that our target regions would be on average 2.3 times larger in H^{13}CO^+ than they are in NH_3 . Although we have no maps of the regions, this appears very unlikely. A different possibility was discussed by Zhou et al. (1989) and Myers & Benson (1983): If the stability of a core is determined by the entire line-broadening, for a gravitationally stable core the critical density should relate to the line-width and size of a molecular core as

$$n_{\text{crit}} \propto (\Delta v/R)^2 \iff \Delta v \propto R \sqrt{n_{\text{crit}}}.$$

To fulfill this criterion the H^{13}CO^+ source size would need to be ~ 7 times smaller than that of NH_3 which again appears to be very unlikely. In this scenario, one could then

conclude that molecular clumps are not gravitationally stable but maybe collapsing already. However, overall collapse is not sure at all from such an analysis, and the clumps could also be fragmenting or only partially collapsing (see discussion in Zhou et al. 1989).

As discussed below in §3.2, a significant fraction of sources exhibits broad line wings in the jet/outflow tracer SiO, which is indicative of early outflow and hence early star formation activity. Since H^{13}CO^+ has a larger critical density it traces denser regions of the gas clumps. With ongoing star formation activity, one expects additional line broadening effects from various physical processes like outflows, infall and potential rotation of embedded accretion disks, all spatially unresolved by the current observations. Most of these effects are likely contributing more strongly in the dense gas components and hence could explain the excess in H^{13}CO^+ line-width.

3.2. SiO(2–1)

One of the aims of this study was to identify how many of the sources would show clear SiO emission caused by molecular outflow activity. SiO is believed to be produced in the gas-phase after sputtering Si-bearing species from the dust grain surfaces when the outflow/jet impinges on the ambient gas and dust (Schilke et al. 1997). SiO is usually barely detectable in quiescent clouds. Figure 4 presents the 18 SiO(2–1) detections toward our source sample of 43 regions. If this source sample is representative for typical Infrared Dark Clouds, this implies that in at least 40% of the IRDCs star formation has already started (absence of SiO emission does not necessarily imply absence of star formation activity). However, it is not obvious whether this sample is representative for all IRDCs because it was selected to be close to sites of already ongoing massive star formation.

Table 2 also lists the width-to-zero-velocity Δv_0 of the observed SiO(2–1) lines. If one divides the observed SiO spectra by their width-to-zero-velocity Δv_0 into 3 regimes (a) low velocity $\Delta v_0 < 10 \text{ km s}^{-1}$, (b) intermediate velocity $10 \text{ km s}^{-1} < \Delta v_0 < 20 \text{ km s}^{-1}$ and (c) high velocity $\Delta v_0 > 20 \text{ km s}^{-1}$, one finds six sources in the low-velocity regime, five at intermediate velocities and seven in the high-velocity regime. While the sources at intermediate to high velocities obviously show gas at relatively high velocities with respect to the ambient gas, this is less clear for the sources in the low-velocity regime: those sources with $\Delta v_0 > 5 \text{ km s}^{-1}$ probably also have outflow contributions, but the SiO(2–1) spectra toward two sources with $\Delta v_0 < 2.5 \text{ km s}^{-1}$ (IRDC 18223-6 & IRDC 18530-2) hardly look like typical outflow spectra. A similar spread in SiO velocities has also previously been observed by, .e.g., Lefloch et al. 1998; Codella et al. 1999. What are possible reasons for the different observed SiO Δv_0 ?

The observed velocity spread could partly be produced by the angles between the outflows and the plane of the sky since we only observe line-of-sight velocities. However, assuming a random distribution of outflow inclination angles θ ($\theta = 0$ is an outflow along the line of sight) and similar unprojected outflow velocities, one would expect fewer outflows at high velocities than at low velocities ($\int_0^{45} \sin(\theta) d\theta \sim 0.29$ vs. $\int_{45}^{90} \sin(\theta) d\theta \sim 0.71$). This is in contrast to our relatively even distribution of Δv_0 from low to high values. Hence, inclination effects are unlikely to explain the observations.

Outflows/jets from massive protostars have intrinsically higher velocities than those of their low-mass counterparts (e.g., Richer et al. 2000). In addition, more luminous sources usually exhibit stronger SiO emission (e.g., Codella et al. 1999). Therefore, the sources with smaller line-width could harbor less massive protostars that may or may not form a massive star at the end of their evolution. Furthermore, all objects with low SiO velocity spread are also the weakest or non-detections in CH₃CN and CH₃OH (see §3.3) which is also expected in the framework of embedded protostars with different masses. Thus, different masses/luminosities of the embedded outflow-driving sources can potentially cause the observed SiO line-width difference.

Since IRDCs are believed to represent the earliest evolutionary stages of massive (and low-mass) star formation, we expect that in some of them low- to intermediate-mass protostars may be embedded that are likely destined to grow, accrete and become high-mass stars at the end of their evolution (e.g., IRDC 18223-3, Beuther et al. 2005b; Beuther & Steinacker 2007). However, a priori we cannot differentiate whether an object will become massive at the end of its evolution or whether it will remain a low-mass protostar. In this scenario, one can also speculate about an evolutionary sequence where the growing protostars accelerates the gas to higher velocities in the course of its early evolution, i.e., the smaller line-widths may correspond to the still less massive and younger objects whereas the broad line-width sources may have already accreted more mass and could hence be a little bit more evolved. This picture is consistent with the above assertion that the line-width distribution can depend on the mass and luminosity of the central object, just with the additional assumption that the lower-mass objects may still be able to become massive stars during their ongoing evolution. This scenario may appear counter-intuitive compared to typical low-mass outflows where the strongest emission is observed from class 0 sources and where the SiO emission gets weaker formore evolved class I and II sources (e.g., Gibb et al. 2004). However, even class 0 sources have typically already ages of the order 10^4 yrs, and IRDCs like those presented here are likely still significantly younger (e.g., Beuther & Steinacker 2007; Krumholz et al. 2007). Furthermore, this low-mass classification scheme is unlikely to be well applicable to high-mass star formation because, among other reasons, massive stars reach the main sequence while accretion processes can still be ongoing (e.g., Schaller et al. 1992; McKee & Tan 2003).

Therefore, our picture applies only to the earliest evolutionary stages of strongly accreting protostars destined to become massive stars at the end of their evolution. In principle, the non-detection of SiO line-wings could also be caused by poorer signal-to-noise ratios or larger distances to the respective region. However, both scenarios are unlikely the case here because we have approximately the same rms for all sources, and the line-width differences are found also toward sources at the same distances (e.g., IRDC 18223-1243-3 & IRDC 18223-1243-4 versus IRDC 18223-1243-6).

Do the $\Delta v_0 < 2.5 \text{ km s}^{-1}$ fit into any of these pictures? Since more than 50% of the target sources exhibit no SiO emission at all down to our sensitivity limit, it is interesting that two objects show these extremely narrow line-widths. Lefloch et al. (1998) and Codella et al. (1999) try to explain similar observations by outflow/dense clump interactions and in an outflow evolutionary model. In the latter scenario, the highest velocity components are found at the earliest evolutionary class 0 stages and the smaller line-width components could be remnants from earlier interactions of molecular outflows with the ambient gas (Codella et al. 1999). They estimated the corresponding time-scale to decrease the SiO emission and the velocities to be of the order 10^4 yrs. We consider this scenario as unlikely for our sample because massive star formation proceeds on relatively short time-scales (of the order 10^5 years, McKee & Tan 2002), and after 10^4 yrs the regions are expected to be strong enough to be detectable at near- and mid-infrared wavelengths (e.g., the samples presented by Molinari et al. 1996 or Sridharan et al. 2002) which is in contrast to our sample selection as Infrared Dark Clouds. Another possibility is to speculate whether these objects could represent the earliest observed stage of star formation within our source sample: In this picture, the Si-bearing species would just be released from the grains by shock interaction and SiO would only have begun to form in the gas phase, but the young jet/outflow would not have had the time yet to accelerate large amounts of gas to detectable higher velocities. To confirm or discard this picture additional indicators of star formation activity would need to be observed, e.g., infall of gas via asymmetric line profiles (e.g., Myers et al. 1996) or shocked H_2 emission either in the K-band (e.g., Davis et al. 2004) or in the IRAC $4.5 \mu\text{m}$ band (e.g., Rathborne et al. 2005).

3.3. $\text{CH}_3\text{CN}(6_k - 5_k)$ and $\text{CH}_3\text{OH}(5-4)$

In addition to the previously discussed molecules, the spectral setup allowed to observe also the typical hot-core tracer CH_3CN as well as a series of four CH_3OH lines. Although the critical densities and excitation parameters of both molecules do not differ that much (see Table 1), CH_3OH typically has one to two orders of magnitude larger gas column

densities and is hence easier to observe (e.g., van Dishoeck & Blake 1998; Nomura & Millar 2004). Furthermore, CH_3OH is known to be present in massive star formation right from the beginning, hence it is a so-called parent molecule, whereas CH_3CN is a daughter molecule which needs time to form through chemical processes during the massive star formation process (e.g., Nomura & Millar 2004). Therefore toward a sample of young IRDCs, one would expect CH_3CN to be either undetectable or only weakly detected in a few sources, whereas CH_3OH should be detectable toward a larger fraction of the sample.

These expectations are largely confirmed by our observations (Figs. 6 & 7), we detect CH_3CN only toward 6 sources ($\sim 14\%$) whereas CH_3OH is observed toward 17 regions ($\sim 40\%$). Furthermore, if detected, $\text{CH}_3\text{CN}(6_k - 5_k)$ is observed only in its two lowest k -components with excitation temperatures < 30 K, the $k = 2$ transition is detected in no source at all. Similarly, for CH_3OH , we detected toward the 17 regions the two lower excitation lines, whereas the two higher excitation lines are detected only toward a small sub-sample of 5 regions. This is additional confirmation of the youth and low average temperatures of the selected source sample. Table 3 lists the line-widths $\Delta\nu_{k=0}$ and $\Delta\nu_{k=1}$ of the CH_3CN $k = 0, 1$ components from Gaussian fits to each line. While we cannot fit one source because of multiple components and in one other source $\Delta\nu_{k=0}$ and $\Delta\nu_{k=1}$ are of approximately equal width, for the four other sources we find consistently larger line-widths in the $k = 1$ component compared to the $k = 0$ component. This is consistent with already ongoing star formation activity in these regions, where the warmer more central gas is subject to more non-thermal motion, either of turbulent nature or due to infall, rotation and/or outflow processes.

One can try to use the observed lines also to get more quantitative temperature and column density estimates. Following Loren & Mundy (1984), assuming optically thin emission and that a single temperature characterizes the populations within a k -ladder and between different k -ladders, the ratios of the intensities of different k lines can be used to estimate this temperature. Specifically, for the $J = 6 - 5$ line and $k = 0$ and $k = 1$ components, we have

$$T = 7.2 / \ln(I_0/I_1)$$

with I_k the corresponding observed peak intensities. For IRDC 18102–1800-1 and IRDC 20081+2720-2, the relative line intensities are consistent with optically thin emission and we estimate the temperatures to be 16 ± 16 and 16 ± 13 K, respectively. For the other sources, while they are unlikely to be optically thick, the intensities are inconsistent with optically thin emission, so we do not estimate temperatures. It is interesting that the estimates, where possible, although not very accurate, turn out to be low and similar to

estimates from NH_3 observations (Sridharan et al. 2005). We cannot use the two mainly detected CH_3OH lines for temperature estimates because they are of different symmetry (A- and E- CH_3OH) and can be considered for radiative transport purposes as distinct molecules.

However, we can calculate the column densities in the detected CH_3OH and CH_3CN lines, and then derive the total molecular column densities following Rohlfs & Wilson (2006). As partition functions we used the values listed in the JPL catalog at $T = 18.75$ K (Poynter & Pickett 1985). Furthermore, we are interested in CH_3OH and CH_3CN molecular abundances. To estimate these, we extracted the 1.2 mm peak fluxes from the images presented in Beuther et al. (2002)¹. Following Hildebrand (1983) and Beuther et al. (2005a), we then calculated the H_2 column densities at $T = 19$ K (corresponding to the partition functions for the molecular emission) assuming optically thin emission and a dust opacity index $\beta = 2$. The spatial resolution of the 1.2 mm and CH_3OH data is approximately the same, for the comparison with the lower-resolution CH_3CN data, we smoothed the 1.2 mm images also to the corresponding spatial resolution of $23''$. The 1.2 mm peak fluxes and H_2 column densities (both at $11''$ resolution) are listed in Table 2. The different H_2 column densities were then used to estimate the CH_3OH and CH_3CN abundances. The calculated molecular column densities are estimated to be correct within a factor 5, the accuracy of the estimated abundances is correspondingly worse. Table 3 lists the derived molecular CH_3OH and CH_3CN column densities and abundances which are on average relatively low.

The average CH_3CN column density and abundance are $3.1 \times 10^{12} \text{ cm}^{-2}$ and 1.2×10^{-10} , respectively. This CH_3CN abundance compares well to the CH_3CN abundance observed for example in the relatively cold and quiescent Orion extended ridge whereas it is two orders of magnitude below the values obtained for the Orion hot core (van Dishoeck & Blake 1998). Furthermore, it fits well to the chemical modeling of young high-mass star-forming regions by Nomura & Millar (2004): they find very low CH_3CN column densities of the order $10^{11} - 10^{12} \text{ cm}^{-2}$ after only a few hundred years which then progressively increase to values $> 10^{15} \text{ cm}^{-2}$ after several 10^5 years. In this picture, even the sources with detected CH_3CN emission are as expected extremely young massive star-forming regions.

The average CH_3OH column density and abundance are $8.2 \times 10^{13} \text{ cm}^{-2}$ and 4.3×10^{-10} , respectively. This abundance is orders of magnitude below the values obtained toward the typical regions in Orion (e.g., 8×10^{-9} for the extended ridge and 2×10^{-7} for the hot core, van Dishoeck & Blake 1998). However, it is very close to the recently reported CH_3OH abundances of 6×10^{-10} in the low-mass starless cores L1498 and L1517B (Tafalla et al.

¹Beuther et al. (2002) presented peak fluxes from 2D Gaussian fits to the images whereas here we use the exact fluxes toward the peak positions. The former are on average a bit lower.

2006). Although the statistics are still small, this similarity between CH_3OH abundances in low-mass starless cores and high-mass IRDCs indicates that the initial CH_3OH molecular abundances at early evolutionary stages do not differ significantly between low- and high-mass star-forming regions.

4. Conclusions and summary

These single-dish mm spectral multi-line observations toward a sample of 43 massive IRDCs revealed a range of interesting results. Since IRDC are expected to harbor sources in different evolutionary stages from genuine HMSCs to High-Mass cores with embedded low- to intermediate-mass protostars potentially destined to become massive stars, it is not surprising that the observational signatures do vary significantly over the sample. Because our spectral line selection covered tracers sensitive to different processes (outflows, dense gas, lower density gas, hot core chemistry) we are able to constrain various characteristics. In summary they are:

- Toward 40% of the sources $\text{SiO}(2-1)$ as a typical outflow/jet tracer was detected. Assuming that SiO is exclusively produced by gas phase reactions after sputtering Si-bearing species from dust grains, this implies that at least 40% of the IRDCs presented here have ongoing star formation activity (non-detection of SiO does not imply no star formation activity, hence the lower limit). The observed width-to-zero-velocity of the SiO lines varies between 2.2 and 65 km s^{-1} . While inclination effects are unlikely to cause this velocity spread, we discuss other potential origins, e.g., embedded objects with different masses and/or possible evolutionary effects.
- While we usually detect many velocity components in the low-density tracers $^{12}\text{CO}(2-1)$ and $^{13}\text{CO}(1-0)$, the high-density tracer $\text{H}^{13}\text{CO}^+(1-0)$ is also present in all except one source, but in general tracing only one velocity component. Therefore, it is well suited to derive velocities with respect to the standard of rest and hence kinematic distances for IRDCs. The observed FWHM line-width of $\text{H}^{13}\text{CO}^+(1-0)$ is on average a factor 1.5 larger than that of the previously observed $\text{NH}_3(1,1)$ line. Several possibilities for that behavior are discussed: While the typical line-width–size relation is unlikely the cause for this behavior, the data are consistent with gravitational instabilities of the cores. However, this interpretation is not unambiguous. Since H^{13}CO^+ has higher critical densities, it traces the denser central cores with likely larger internal motions. This motions could be caused by turbulence or by active star formation processes like outflows/infall, rotation.

- As expected CH_3CN is only rarely detected (toward $\sim 14\%$ of the sources), whereas CH_3OH is observed toward a larger fraction of the sample ($\sim 40\%$). Both molecules are only detected in their lower-energy transitions. While temperature estimates are hardly feasible with these data, we are able to derive the CH_3CN and CH_3OH abundances with average values of 1.2×10^{-10} and 4.3×10^{-10} , respectively. The low CH_3CN column densities are consistent with chemical models where the CH_3CN abundances are very low at the earliest evolutionary stages and progressively increase with time. The derived CH_3OH abundances are close to recently reported values for low-mass starless cores, indicating that the initial CH_3OH abundances at the onset of star formation processes do not vary significantly from low- to high-mass cores.

We like to thank Sven Thorwirth for continuous spectroscopic help. H.B. acknowledges financial support by the Emmy-Noether-Program of the Deutsche Forschungsgemeinschaft (DFG, grant BE2578).

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Table 2:: Source parameters

Name	R.A. J2000	Dec. J2000	D ^a kpc	$v(\text{H}^{13}\text{CO}^+)$ km s ⁻¹	$\Delta v(\text{H}^{13}\text{CO}^+)$ km s ⁻¹	$\Delta v_0(\text{SiO})^b$ km s ⁻¹	$S_{1.2\text{mm}}^c$ $\frac{\text{mJy}}{(11'')^2}$	$N_{\text{H}_2}^d$ $\frac{10^{23}}{\text{cm}^2}$
IRDC18089–1732-3	18 11 45.3	–17 30 38	3.6	34.2(0.1)	3.9(0.2)	5.5	147	1.5
IRDC18090–1832-2	18 12 02.0	–18 31 27	6.6	111.2(0.1)	2.2(0.2)		89	0.9
IRDC18102–1800-1	18 13 11.0	–18 00 23	2.7 ^e	21.4(0.1)	3.4(0.1)	42.2	632	6.3
IRDC18151–1208-2	18 17 50.3	–12 07 54	3.0	29.8(0.1)	3.0(0.1)	65.0	620	6.2
IRDC18182–1433-2	18 21 14.9	–14 33 06	3.6	40.9(0.1)	2.2(0.1)		144	1.4
IRDC18182–1433-3	18 21 17.5	–14 29 43	4.6 ^e	60.2(0.1)	1.7(0.3)	5.5		
IRDC18182–1433-4	18 21 14.0	–14 34 20	3.6	41.4(0.1)	2.0(0.2)			
IRDC18223–1243-2	18 25 10.0	–12 44 00	3.7	45.5(0.1)	3.4(0.1)		156	1.6
IRDC18223–1243-3	18 25 08.3	–12 45 27	3.7	45.7(0.1)	2.7(0.1)	35.5	289	2.9
IRDC18223–1243-4	18 25 06.8	–12 48 00	3.7	45.7(0.1)	2.4(0.1)	38.9	77	0.8
IRDC18223–1243-5	18 25 12.0	–12 53 23	3.7	45.1(0.2)	1.7(0.2)			
IRDC18223–1243-6 ^f	18 25 16.2	–12 55 33	3.7	45.7(0.1)	2.0(0.3)	2.4		
IRDC18223–1243-6 ^f	18 25 16.2	–12 55 33	3.7	50.9(0.2)	2.1(0.4)			
IRDC18247–1147-3	18 27 31.0	–11 44 46	6.7	59.7(0.2)	2.2(0.6)		110	1.1
IRDC18306–0835-3	18 33 32.1	–08 32 28	3.8 ^e	54.8(0.1)	2.4(0.1)		154	1.5
IRDC18306–0835-4	18 33 34.8	–08 31 20	3.8 ^e	55.2(0.1)	2.4(0.2)			
IRDC18337–0743-3	18 36 18.2	–07 41 00	4.0	56.2(0.1)	2.8(0.1)	39.8	123	1.2
IRDC18337–0743-4	18 36 29.9	–07 42 05	4.0	55.8(0.1)	4.2(0.3)			
IRDC18337–0743-5	18 36 41.0	–07 39 56	4.0	58.4(0.1)	4.1(0.2)	16.2		
IRDC18337–0743-6	18 36 36.0	–07 42 17	4.0	56.6(0.1)	2.5(0.2)			
IRDC18337–0743-7	18 36 19.0	–07 41 48	4.0	55.9(0.1)	2.7(0.2)			
IRDC18348–0616-2	18 37 27.6	–06 14 08	6.3	109.7(0.1)	2.6(0.1)	9.9	169	1.7
IRDC18348–0616-8	18 37 14.7	–06 17 25	6.3	109.3(0.2)	4.4(0.4)			
IRDC18385–0512-3	18 41 17.4	–05 10 03	3.3 ^e	47.0(0.1)	2.1(0.1)	41.1	77	0.8
IRDC18431–0312-3	18 45 45.0	–03 08 56	6.6 ^e	105.4(0.3)	2.2(0.7)			
IRDC18431–0312-4	18 45 53.0	–03 09 01		non det.	non det.			
IRDC18437–0216-3 ^f	18 46 21.9	–02 12 24	6.2 ^e	97.6(0.2)	2.1(0.4)		96	1.0
IRDC18437–0216-3 ^f	18 46 21.9	–02 12 24	7.3 ^e	111.3(0.1)	2.3(0.4)		96	1.0
IRDC18437–0216-7 ^f	18 46 22.0	–02 14 10	6.2 ^e	96.1(0.1)	2.9(0.1)	13.0		
IRDC18437–0216-7 ^f	18 46 22.0	–02 14 10	7.3 ^e	111.2(0.7)	1.9(1.8)			
IRDC18440–0148-2	18 46 31.0	–01 47 08	5.6 ^e	97.9(0.2)	2.9(0.4)			
IRDC18447–0229-3	18 47 42.0	–02 25 12	6.4 ^e	102.1(0.2)	2.6(0.5)			
IRDC18447–0229-4	18 47 38.9	–02 28 00	6.4 ^e	99.4(0.1)	1.9(0.3)			
IRDC18454–0158-1 ^f	18 48 02.1	–01 53 56	3.5 ^e	52.8(0.4)	1.7(0.7)		178	1.8
IRDC18454–0158-1 ^f	18 48 02.1	–01 53 56	6.4 ^e	100.2(0.1)	2.7(0.2)	10.9	178	1.8
IRDC18454–0158-3 ^f	18 47 55.8	–01 53 34	6.0 ^e	94.3(0.1)	3.5(0.3)	17.3 ^g	204	2.0
IRDC18454–0158-3 ^f	18 47 55.8	–01 53 34	6.4 ^e	98.4(0.1)	3.3(0.3)	17.3 ^g	204	2.0
IRDC18454–0158-5	18 47 58.1	–01 56 10	6.0 ^e	94.6(0.1)	2.7(0.1)	17.8	102	1.0
IRDC18454–0158-12 ^f	18 48 05.7	–01 53 28	3.1 ^e	46.3(0.4)	2.5(0.8)			
IRDC18454–0158-12 ^f	18 48 05.7	–01 53 28	6.4 ^e	101.4(0.1)	2.7(0.3)			
IRDC18460–0307-3	18 48 36.0	–03 03 49	5.2	84.6(0.1)	1.8(0.2)		84	0.8

IRDC18460–0307-4	18 48 46.0	–03 04 05	5.2	84.4(0.1)	2.4(0.3)		177	1.8
IRDC18460–0307-5	18 48 47.0	–03 01 29	5.2	84.0(0.1)	2.1(0.1)		74	0.7
IRDC18530+0215-2	18 55 29.0	+02 17 43	5.0 ^e	75.9(0.1)	2.1(0.2)	2.2		
IRDC19175+1357-3	19 19 52.1	+14 01 52	1.1	7.7(0.2)	2.9(0.7)		53	0.5
IRDC19175+1357-4	19 19 50.6	+14 01 22	1.1	7.8(0.1)	2.1(0.2)		87	0.9
IRDC19410+2336-2	19 43 10.2	+23 45 04	2.1	21.5(0.1)	2.3(0.1)	36.8 ^h	343	3.4
IRDC20081+2720-1	20 10 13.0	+27 28 18	0.7	5.7(0.1)	1.8(0.1)		244	2.4
IRDC22570+5912-3	22 58 55.1	+59 28 33	5.1	-47.5(0.1)	2.8(0.1)	5.5	88	0.9

^a Most distances are taken from Sridharan et al. (2005). The exceptions are marked.

^b Width of SiO(2–1) line down to zero intensity.

^c Here we present the 1.2 mm peak fluxes extracted directly from the peak positions. In the original paper, Beuther et al. (2002) present peak fluxes from 2D Gaussian fits which are on average a bit lower.

^d The column density calculations follow Beuther et al. (2005a) at an average temperature of 19 K to be better comparable with the CH₃OH and CH₃CN column densities calculated at $T = 18.75$. Masses and integrated fluxes were already presented in Sridharan et al. (2005).

^e Newly derived near kinematic distances following Brand & Blitz (1993) because IRDCs at the far distances are unlikely.

^f Rows with the same IRDC name correspond to different H¹³CO⁺ velocity components.

^g This is a line-blend between both velocity components.

^h The outflow was studied in detail by Beuther et al. (2003).

Table 3: CH₃CN and CH₃OH parameters.

Name	$\Delta v_{k=0}^a$ km s ⁻¹	$\Delta v_{k=1}^a$ km s ⁻¹	$N_{\text{CH}_3\text{CN}}$ 10 ¹² cm ⁻²	$X_{\text{CH}_3\text{CN}}$ 10 ⁻¹⁰	$N_{\text{CH}_3\text{OH}}$ 10 ¹³ cm ⁻²	$X_{\text{CH}_3\text{OH}}$ 10 ⁻¹⁰
IRDC18102–1800-1	2.9(0.4)	3.9(0.8)	2.6	0.3	2.8	0.4
IRDC18151–1208-2	3.4(0.3)	4.5(0.5)	5.3	0.8	37.2	6.0
IRDC18182–1433-2					3.0	2.1
IRDC18223–1243-3	2.8(0.5)	3.1(0.5)	2.7	0.9	17.6	6.1
IRDC18223–1243-4					4.6	6.0
IRDC18337–0743-3	3.1(0.9)	6.2(1.4)	4.4	3.6	13.1	10.7
IRDC18385–0512-3					5.3	6.9
IRDC18437–0216-7					2.5	–
IRDC18454–0158-1					1.7	0.9
IRDC18454–0158-1					1.7	0.9
IRDC18454–0158-3	? ^b	? ^b			11.1	5.5
IRDC18454–0158-3	? ^b	? ^b			11.1	5.5
IRDC19175+1357-4					4.3	5.0
IRDC19410+2336-2					5.0	1.5
IRDC20081+2720-1	1.4(0.3)	1.3(0.4)	0.7	0.3		
IRDC22570+5912-3					2.4	2.8

^a Line-width of the CH₃CN $k = 0$ and $k = 1$ components.

^b No reasonable fits because of multiple velocity components.

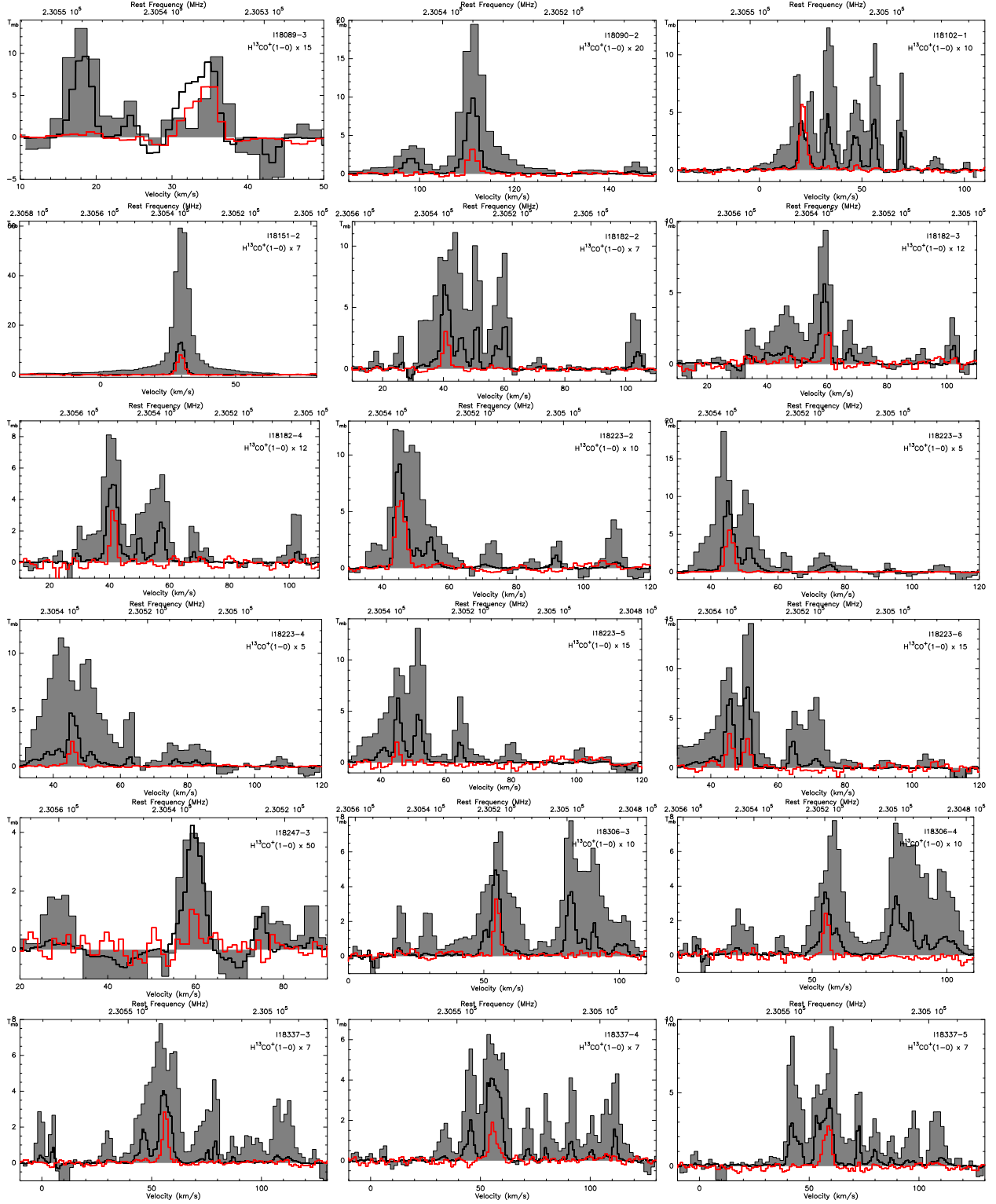


Fig. 1.— $^{12}\text{CO}(2-1)$ (grey), $^{13}\text{CO}(1-0)$ (black line) and $\text{H}^{13}\text{CO}^+(1-0)$ (red line) spectra toward the whole sample of IRDCs. The $\text{H}^{13}\text{CO}^+(1-0)$ are scaled up by the factor labeled in each panel for presentation purposes.

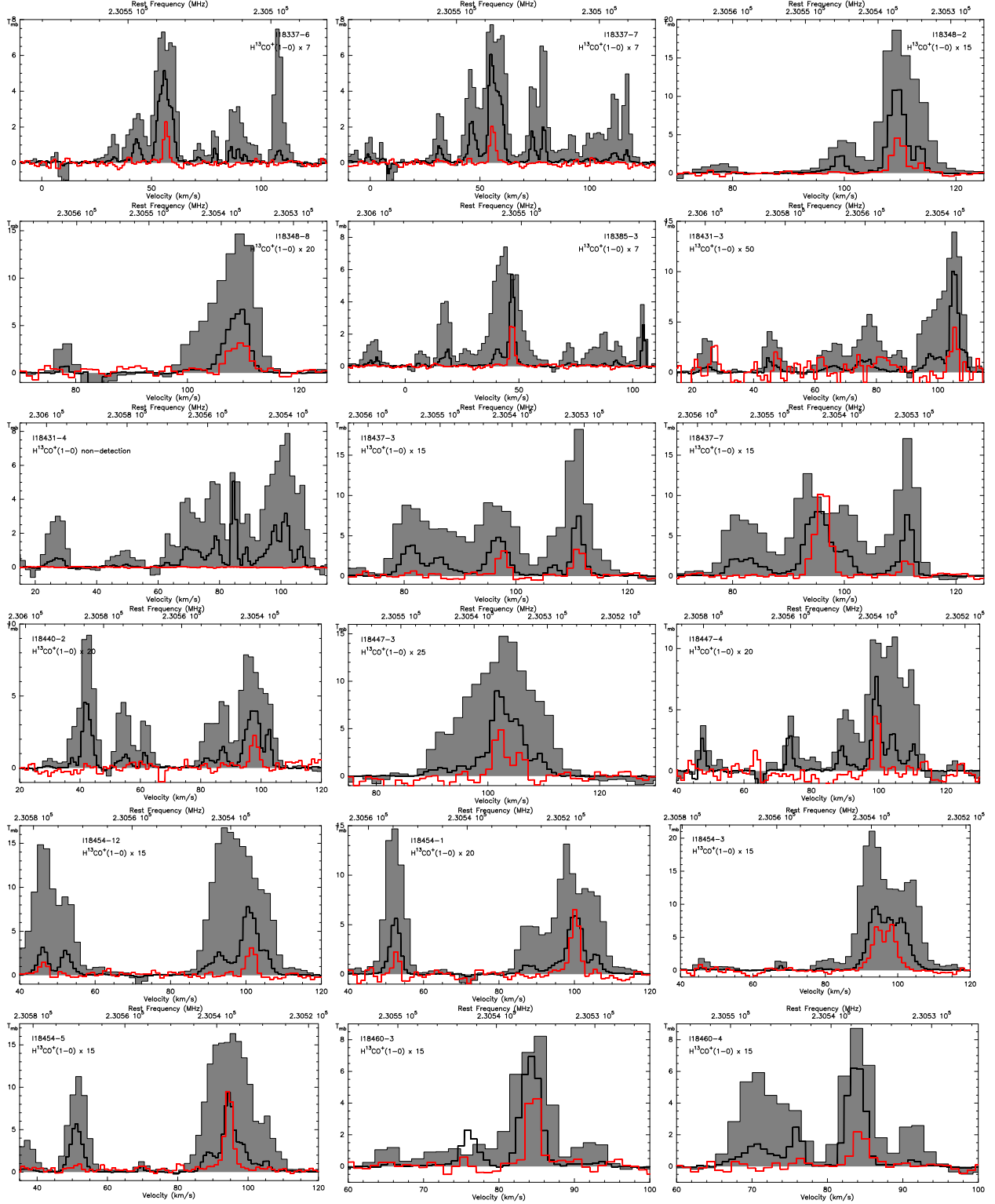


Fig. 2.— Figure 1 continued.

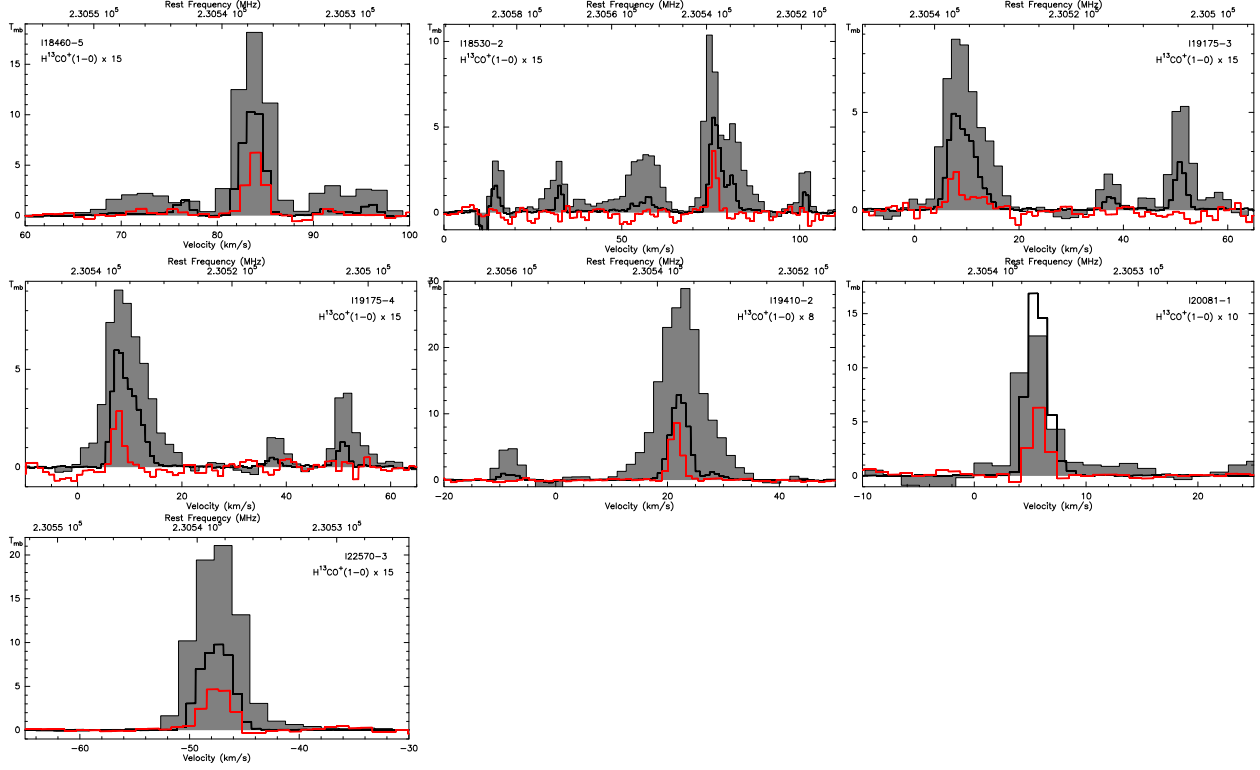


Fig. 3.— Figures 1 & 2 continued.

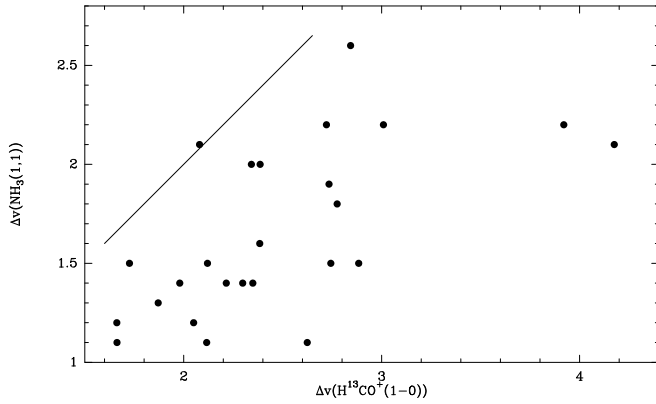


Fig. 4.— Comparison of line-widths between $\text{H}^{13}\text{CO}^+(1-0)$ (this work) and $\text{NH}_3(1,1)$ (Sridharan et al. 2005).

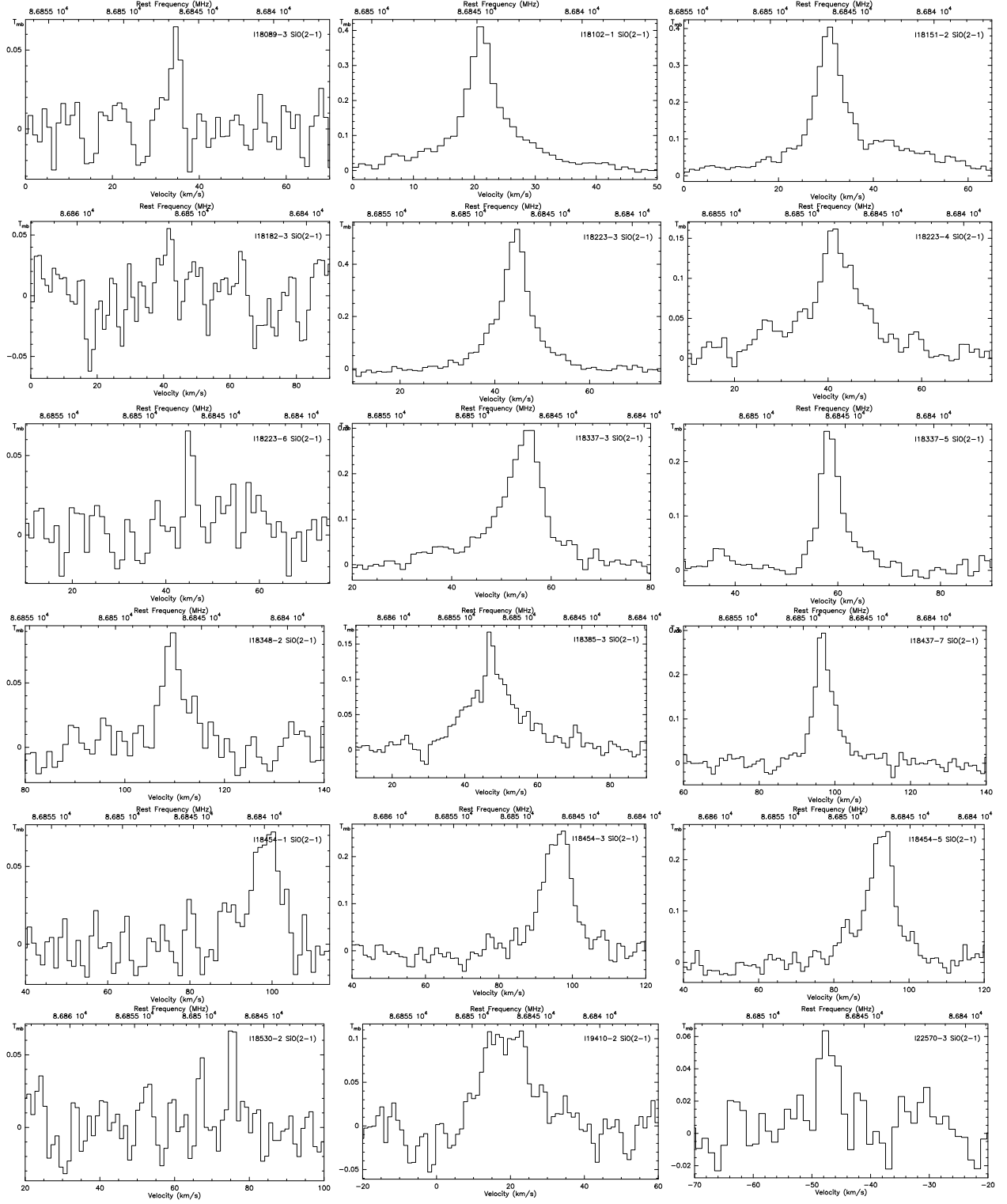


Fig. 5.— SiO(2-1) detections.

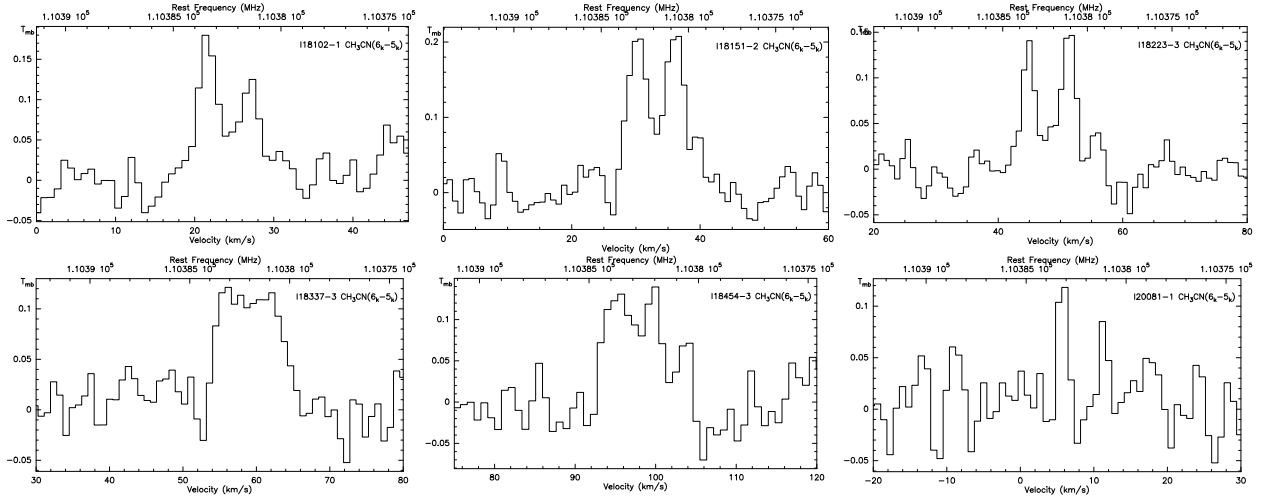


Fig. 6.— $\text{CH}_3\text{CN}(6_k - 5_k)$ detections. The rest frequencies of the $k = 0, 1, 2$ components are at 110383.522, 110381.404 and 110375.052 MHz, respectively. Because of the small intrinsic line-widths, the $k = 0, 1$ components are spectrally resolved which is usually not the case for more evolved High-Mass Protostellar Objects or Hot Molecular Cores.

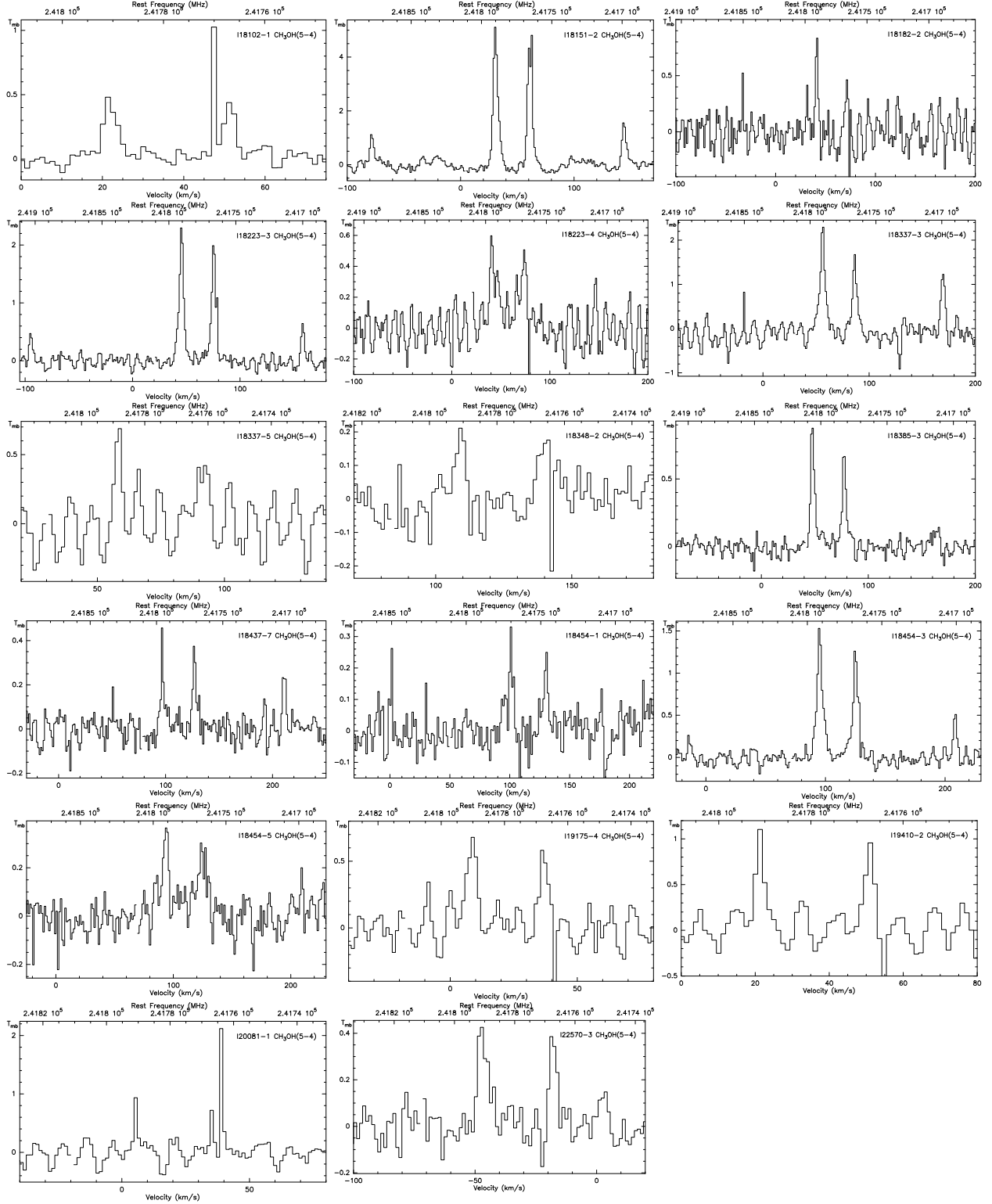


Fig. 7.— $\text{CH}_3\text{O}(5-4)$ detections. The rest frequencies of the four detected lines are: $\text{CH}_3\text{OH}(5_1-4_1)\text{E}$ at 241879.073 MHz, $\text{CH}_3\text{OH}(5_0-4_0)\text{A}+$ at 241791.431 MHz, $\text{CH}_3\text{OH}(5_{-1}-4_{-1})\text{E}$ at 241767.224 MHz, $\text{CH}_3\text{OH}(5_0-4_0)\text{E}$ at 241700.219 MHz. The few single-channel spikes are artifacts caused by the correlator.